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OPTIMIZATION DESIGN OF END CARRIAGE OF THE SINGLE-GIRDER BRIDGE CRANE STRUCTURE

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***Key words**: bridge crane, end carriage, metaheuristic, optimization design*

***Abstract:** In the structure of the bridge cranes, end carriages have very important functions and importance. These segments of the bridge crane structure must ensure the stable movement of the main girder of the bridge crane along the crane runway beam. For this reason, they also have a greater responsibility in the structural stability of the bridge crane, so the choice of the geometric characteristics of the cross-section of these segments is of great importance, which is reflected primarily in theirs stiffness, as well as the connection of these segments with the main girder of the bridge crane. In this research, the analysis and optimization of the box cross-section of the welded girder of end carriage will be carried out and the justification of this approach in terms of material savings will be justified. Examples of two single-girder bridge cranes in which are in exploitation will be used for the calculation. One metaheuristic algorithm will be used as a methodology for the optimization process, since such methods have been increasingly used lately, especially in engineering problems.*

1. INTRODUCTION

For manipulation of bridge cranes along the crane track (translational movement), when performing the functions for which they are intended, an appropriate drive for this movement is necessary, as well as a type of structure. For this reason, end carriages are used, which together with the main girder form the steel structure of the bridge crane, and have the task of translating the entire structure of the bridge crane along the crane track, as well as to ensure stability and rigidity of the whole bridge crane structure.

For these reasons, end carriages have a greater responsibility in the whole structure of the bridge crane, so the choice of geometric characteristics of the cross-section of these girders is of great importance. Box profiles (both standard and welded, depending on the load capacity) are most often used for end carriage constructions, although other forms of profiles are also used.

Regarding the analysis of end carriages of bridge cranes, the FEM analysis of the structure of the whole bridge crane end carriages and the main girder) is most often performed, to notice the places where the greatest stresses occur, as shown in papers [01] and [02]. The influence of the change of stress states along with end carriages, depending on the crane capacity, is shown in the paper [03], on the example of the single-beam bridge crane.

The determination of the longitudinal force on the wheels of the end carriage is presented in the paper [04], where a model for solving this problem is presented, where it is defined how the geometrical characteristics of the end carriage affect the magnitude of this force.

For optimization procedures of welded structures, from the standpoint of weight and price, many publications deal with this issue. Also, there are more and more different procedures and methods that are applied to engineering optimization problems. In the paper [05], the weight optimization of the welded I girder of the double-beam bridge crane was performed using Ms. EXCEL. Various metaheuristic algorithms are increasingly used in optimization problems, as shown in papers [06] and [07], on the examples of welded structures. In the paper [06], APSO, CS, and FA algorithms were applied to optimize the weight of the welded structure of the boom of the column-mounted jib crane, while in the paper [07] a modified ABC algorithm was applied, which aims to reduce the cost of different types of welded structures.

In this research, the box cross-section of the welded end carriage will be optimized and the justification of the proposed approach in terms of material savings will be shown, compared to the standard design.

2. OPTIMIZATION PROBLEM

The following figures show the model of static analysis of the structure of the single-beam bridge crane (Fig.1), as well as the static model of end carriage (Fig.2). The determination of all static parameters will be shown in the next part of the paper.

In this research, the analysis and optimization of the the welded end carriage structure (Fig.2) will be performed based on the model and method that will be presented below.

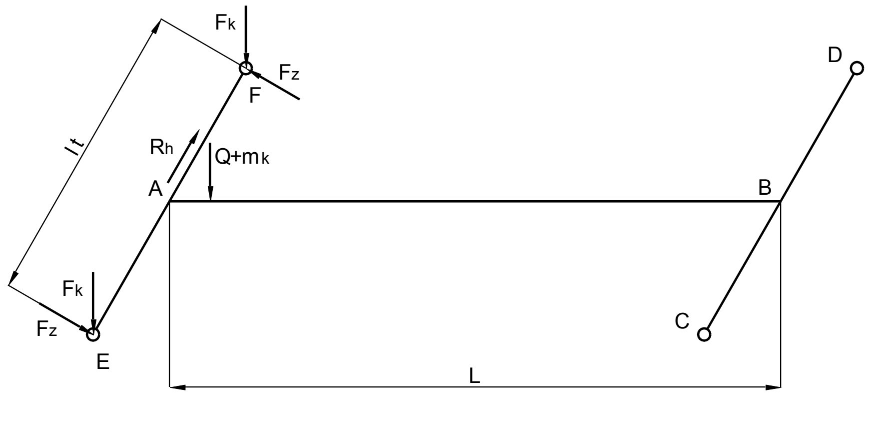

Fig.1 – The static model for single-beam bridge crane

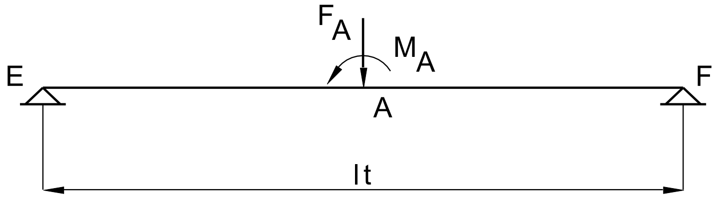

Fig.2 – The static model for end carriage

In this paper, one metaheuristic nature-inspired algorithm for global optimization, called Multi-Verse Optimizer (MVO), are taken for optimization process. Multi-Verse Optimizer (MVO) was introduced in the paper [08], as an efficient population-based algorithm, inspired by nature. Inspirations for the MVO are based on three concepts in cosmology: white hole, black hole, and wormhole, and the mathematical models of these concepts are developed to perform exploration, exploitation, and local search, respectively.

The mathematical formulation of the objective function is:

$$f(X) = A(x_1, \dots x_n) = (b_1, t, h, s) \qquad (1)$$

where the parameter x_i presents the optimization variable (values that should be defined during the optimization procedure - defined by its upper and lower boundaries).

The input parameters for this optimization problem are:

$$\left(Q,\ L,\ l_t,\ m_k,\ e_1,\ D_t,\ b_t, \dots\right) \qquad (2)$$

where:

Q - the carrying capacity of the crane

L - the span of the crane

l_t - end carriage wheelbase

m_k - the weight of the trolley

e_1 - the distance between the trolley wheel and the resulting force

$D_t,\ b_t$ - the diameter and the width of an end carriage wheel, respectively

b_s - the width of the rail

Below will be present the objective function and optimization criteria, respectively.

3. THE OBJECTIVE FUNCTION

The objective function is represented by the area of the box cross-section (Fig.3).

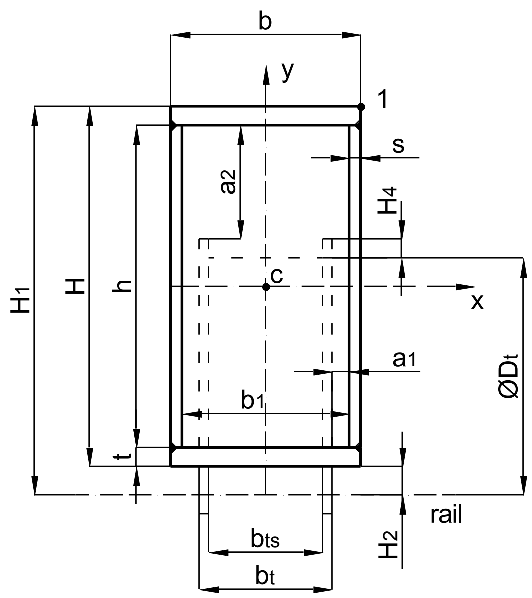

Fig.3 – Box cross-section of end carriage

The cross-sectional area, i.e. the objective function, is:

$$A = 2 \cdot \left(b \cdot t + h \cdot s\right)\ (cm^2) \qquad (3)$$

The weight of end carriage is:

$$m_c = 1{,}1 \cdot A \cdot l_t \cdot \rho \qquad (4)$$

The geometrical properties of the box cross-section shall be determined by well-known expressions (I_x, W_x, W_y). Other geometrical parameters are shown in Fig.3.

4. OPTIMIZATION CRITERIA

4.1 The criterion of strength

The values of bending moments in the corresponding planes, as well as forces are calculated in following way (Fig.1 and Fig.2), according to [09]:

$$F_A = \left[\gamma \cdot (\psi \cdot Q + m_k) \cdot (L - e_1) / L + 0{,}5 \cdot m_n\right] \cdot g \quad (5)$$

$$R_h = k_a \cdot (Q + m_k) \cdot g \quad (6)$$

$$M_A = \gamma \cdot R_h \cdot (y_c - t_2) \cdot (L - e_1) / L \quad (7)$$

$$F_k = 0{,}5 \cdot \left[Q + m_k + m_c + 0{,}5 \cdot m_n\right] \cdot g \quad (8)$$

$$\lambda = \lambda\left(b_{ts} - b_s,\ L / l_t\right) \quad (9)$$

$$F_z = \lambda \cdot F_k \quad (10)$$

$$F_E = 0{,}5 \cdot F_A \cdot l_t + M_A / l_t \quad (11)$$

$$M_v = 0{,}5 \cdot F_E \cdot l_t \quad (12)$$

$$M_h = 0{,}5 \cdot F_z \cdot l_t \quad (13)$$

where:

$F_A,\ M_A$ - the acting force and moment in the middle of end carriage, respectively

$\gamma,\ \psi,\ k_a$ - coefficients, according to [09]

$y_c,\ t_2$ - geometrical parameters of the main girder of the single-beam bridge crane

m_n - the weight of the main girder of the single-beam bridge crane

R_h - the resulting force in the horizontal plane

F_k - the maximum pressure on the end carriage wheel

λ - the coefficient who depends of parameters: $b_{ts},\ b_s,\ L,\ l_t$, accoredind to [09]

F_z - the transverse horizontal wheel force

F_E - the reacting force at point E

$M_v,\ M_h$ - the bending moments in the vertical and horizontal planes, respectively

Maximum stress at point 1 is:

$$\sigma_u = M_v / W_x + M_h / W_y \le \sigma_d = R_e / \nu_1 \quad (14)$$

where:

$R_e = 35{,}5\, kN / cm^2$ - the minimum yield stress of the girder material

$\nu_1 = 1{,}5$ - the factored load coefficient for load case 1

4.2 The criterion of local buckling of plates

Check for local buckling of the web plates of the box cross-section is done according to [10]:

$$M_{v,w} = M_v \cdot h / H \quad (15)$$

$$\sigma_w = \nu_1 \cdot \left(M_{v,w} / W_x + M_h / W_y\right) \le \min\left(\sigma_{d,w},\ R_e\right) \quad (16)$$

$$\sigma_{d,w} = \kappa_w \cdot C_w \cdot R_e \quad (17)$$

where:

$\kappa_w,\ C_w$ - coefficients for web plates, according to [10]

Check for local buckling of the top flange of the box cross-section is done according to [10]:

$$\sigma_p = \nu_1 \cdot \left(M_v / W_x + M_h / W_y \right) \le \min\left(\sigma_{d,p},\ R_e \right) \quad (18)$$

$$\sigma_{d,p} = \kappa_p \cdot C_p \cdot R_e \quad (19)$$

where:

$\kappa_p,\ C_p$ - coefficients for the top flange, according to [10]

4.3 The criterion of stiffness

For this criterion, the maximum deflection of an end carriage *f* must have the value smaller than the permissible one, f_{dop}:

$$f = F_A \cdot l_t^3 / \left(48 \cdot E \cdot I_x \right) \le f_{dop} = K_f \cdot l_t \quad (20)$$

where:

$K_f = 1/1000$ - the coefficient of the stiffness of an end carriage

5. RESULTS OF OPTIMIZATION

In this research, the optimization process was done using one metaheuristic algorithm based on nature, Multi-Verse Optimizer (MVO). Optimization variables are geometrical parameters of the box cross-section: b_1, t, h, s (Fig.3). In addition to the above criteria, geometric constraints should be considered, according to the following equations:

$$b_1 \ge b_t + 2 \cdot a_1 \quad (21)$$

$$H_1 \ge D_t + H_4 + a_2 + t \quad (22)$$

The minimum thickness of the web plates was adopted to be 5 *mm* and the minimum thickness of the flanges was adopted to be 6 *mm*, which are also the constraint functions (additional criteria). Another additional criterion was taken that the maximum values of the width of the flanges are less than *300 mm*. Also, the research will be considered the value of maximum girder height (*H*), whereby to be observed and the case that the height less than that of the standard end carriage. (H_{max}, Table 1).

The input parameters for the optimization process are shown in Table 1 and Table 2 and were taken based on the project documentation for two examples of bridge cranes. Other parameters are taken according to [09]. Both cranes are in classification class 2, according to [09].

Table 1

A_c (cm^2)	$H_2 = H_4$(cm)	D_t (cm)	b_t (cm)	a_1 (cm)	a_2 (cm)	H_{max} (cm)
92,57	1,5	20	12,7	2	4	30

Table 2

Ex.	Q (t)	L (m)	m_n (kg)	k_a	l_t (m)	m_k (kg)	e_1 (cm)	b_{ts} (cm)	b_s (cm)	y_c (cm)	t_2 (cm)
1.	8	15,1	2800	0,08	2,7	610	35,4	6,5	5	31,62	2
2.	10	16,8	3770	0,1	2,5	880	30	7,4	6	33,2	2,5

Table 3 shows the optimization results for the welded end carriage (optimal geometrical values, savings, and optimization parameters of convergence curves) for two examples of the single-beam bridge cranes, where A_{opt} is the optimal value of the welded box cross-sectional area.

Table 3

Ex.	Height constraint	b_1 (cm)	t (cm)	h (cm)	s (cm)	Std	Worst (cm^2)	Mean (cm^2)	Best (A_{opt}) (cm^2)	Saving (%)
1	without	16,7021	0,6000	31,6729	0,5000	1,1992	61,4156	54,1169	52,9155	42,84
	with	22,8718	0,6000	28,7971	0,5000	2,5503	73,1628	58,4696	57,4433	37,95
2	without	16,7005	0,6001	32,9650	0,5000	1,5397	71,6011	55,5468	54,2105	41,44
	with	25,9185	0,6000	28,7967	0,5000	2,0717	70,9292	63,7072	61,0988	34,00

6. CONCLUSION

This paper presents the analysis and optimization for the box-section of the welded end carriage structure, using Multi-Verse Optimizer (MVO). The criteria of strength, local buckling of plates, stiffness, minimum plate thicknesses, and other geometric constraints were applied as the constraint functions for the optimization process. The goal of this research is the minimization of the box cross-sectional area of the welded end carriage.

As can be seen from Table 3, the proposed optimization model and used method (MVO) has achieved significant material savings (within the range 34 ÷ 42,84%), when welding and standard girders are compared. Also, it is noticed that the savings are greater when there is without height constraint, and the optimal cross-sectional area is then reduced by about 10%.

The proposed optimization procedure allows us to quickly reach the necessary dimensions of box girders, which can be very useful for designers of these types of structures. It may also be important for further research, in order to obtain an even better model for optimization, by taking into account the following criteria: conditions of crane control and operation, time of damping of oscillation of the girder, lateral stability of the girder, maximum stress in welded connections, material fatigue, the cost of production and material, etc.

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ОПТИМИЗАЦИОННО ПРОЕКТИРАНЕ НА КРАНОВА КОЛИЧКА ОТ КОНСТРУКЦИЯТА НА КРАН МОСТОВ ЕДНОГРЕДОВ

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Ключови думи: *мостов кран, кранова количка, метаевристика, оптимизационно проектиране*

Резюме: *В конструкцията на мостовите кранове крановите колички имат много важни функции и значение. Тези елементи от конструкцията на мостовия кран трябва да осигуряват устойчиво движение на основния носач на мостовия кран по дължината на мостовия път. Поради тази причина те носят и по-голяма отговорност в конструктивната стабилност на мостовия кран, така че изборът на геометричните характеристики на напречното сечение на тези елементи е от голямо значение, което се отразява предимно в тяхната твърдост, както и връзката на тези сегменти с основната греда на мостовия кран. В това изследване е извършен анализ и оптимизация на напречното сечение на заварения носач на крановата количка и е направена икономическа обосновката ра реализацията на този подход. При изчислението са използвани примери за два едногредови мостови крана. Един метаевристичен алгоритъм е използван като методология за процеса на оптимизация, тъй като напоследък такива методи се използват все по-често, особено при инженерни проблеми.*